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Field Applications of
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16. ABSTRACT Two municipal supply wells in Lakewood, Washington, were found to be contaminated with trichloroethylene, transdichloroethylene, and tetrachloroethylene. Sequential samples were taken for chemical analyses, in conjunction with drawdown measurement during aquifer (pump) tests designed to help characterize the problem site. Plots of the chemical concentrations against duration (or volume) or pumping yielded patterns which lent insight into the orientation of the contaminant source. Analogies are drawn here between interpretation of these chemical time-series patterns and interpretations of breakthrough curves in tracer experiments. Examination of the data also infer the distinct possibility of serious interpretation errors arising from conventional sampling.		
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FIELD APPLICATIONS OF CHEMICAL TIME-SERIES SAMPLING

Discusses a data-gathering scheme with a decreased frequency of sampling
as pumpage continues.

by Joseph F. Keely and Fred Wolf

Introduction

As an outgrowth of emerging concerns over organic chemicals released to surface water by industrial municipal discharges, the Natural Resource Defense Council brought suit against the U.S. EPA administrator (NRDC vs. Train; 8 ERC 2120; D.D.C. 1976). The consent decree reached in settlement of the suit prompted U.S. EPA to issue a list defining 114 organic chemicals, 13 heavy metals, asbestos and cyanide as "priority pollutants" to be regulated under effluent guidelines because of their toxicity to humans and aquatic life, and known or suspected carcinogenic, teratogenic or mutagenic properties. In turn, this list of 129 priority pollutants spilled over into other programs administered by EPA, particularly drinking water and hazardous waste programs.

By late 1978, the first National Organics Reconnaissance Survey (NORS) was set in motion by the EPA Office of Drinking Water to evaluate the prevalence of organic contaminants in drinking-water supplies. A follow-up of NORS in 1980 focused exclusively on ground-water supplies. One of the supply systems randomly selected for inclusion in the 1980 follow-up study was the Lakewood Water District in Washington State. Based on grab samples, water discharged from Lakewood Water District's Well H-1 were found to be contaminated with up to 10 $\mu\text{g/L}$ trichloroethylene, 18 $\mu\text{g/L}$ tetrachloroethylene and 61 $\mu\text{g/L}$ 1,2 trans-dichloroethylene (EPA Region 10 1980). Given that the EPA Assistant Administrator for Drinking Water had just issued Suggested No Adverse Response Levels (SNARLs—toxicologically-based health advisories) regarding the acute/10-day and chronic/lifetime exposure limits of trichloroethylene and tetrachloroethylene due to their deleterious effects on liver and kidney cellular functions (Kimm 1980a and 1980b), the Region 10 EPA Drinking-Water Programs Branch initiated a detailed study to ascertain the potential threat to Lakewood Water District consumers.

Based on discussions with Wayne Dunbar, manager of the Lakewood Water District, the lead author postulated that the source of the contaminants might be inside Well H-1 since it had undergone maintenance just prior to the 1980 sampling. If cleaning solvents had been used to assist in removing excess oils and lubricants from the pump column prior to its reintroduction

to the borehole, then residues might persist and explain the contaminant observations. In part, this line of reasoning was spurred on by the recent publication of an article alerting investigators to such possible contaminant sources (Pettyjohn and others 1981). The hypothesis seemed plausible enough, but how should it be tested?

Hydrologic and chemical intuition, as well as preliminary calculations of the impact of casing water following the method presented by Papadopoulos and Cooper (1967), indicated that concentrations of contaminants in water discharged from Well H-1 should rapidly diminish with time from the onset of pumpage. While the well was inactive, solvent residues would bleed into the water standing in the well casing and slowly attain some maximum equilibrium concentration(s). When the well was pumped, the casing water would be rapidly voided and soon the discharging water would be comprised solely of waters which had been residing in the production zone, wholly external to the well. A plot of organic chemical concentrations vs. time would thus appear to be a rapidly decaying curve. The most efficient data-gathering scheme, then, should focus on collection of several samples just after start-up of Well H-1, with a decreased frequency of sampling as pumpage continued.

The similarity of the proposed sampling scheme with that of conventional pumping tests was noted, so a suggestion was made that water-level measurements be taken concurrently at a companion well (Well H-2) located 80 feet away. Indeed, it was further noted, the transmissivity and storage coefficient resulting from the concurrent pumping test would prove invaluable should the initial hypothesis not be supported by the chemical analyses. The storage coefficient, for example, might indicate whether the aquifer is of the artesian variety and thereby somewhat protected from the downward migration of contaminants from surface activities by an impermeable confining stratum. Dense glacial till layers ("hardpan" in drillers' parlance) had been encountered in drilling each well, though the location and thickness of the till were substantially different for Well H-1 vs. Well H-2 (Figure 1); both wells had been constructed by the same driller and tested by the same engineer (Robinson, 1951 and 1959).

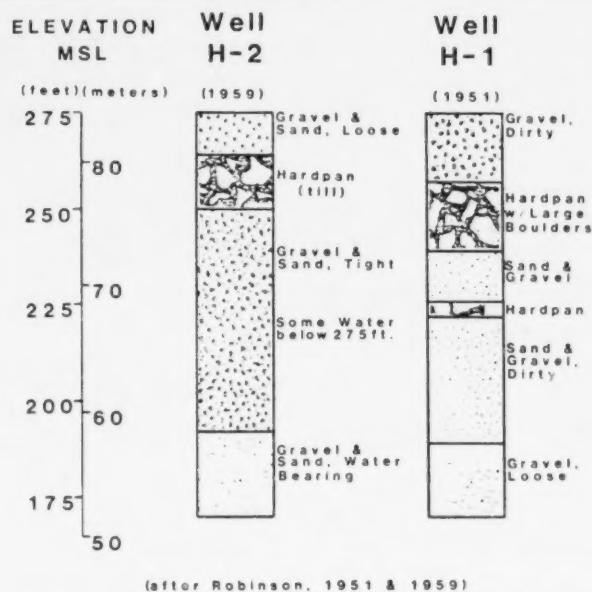


Figure 1. Comparison of driller's logs for Well H-1 and Well H-2 (data from Robinson 1951 and 1959)

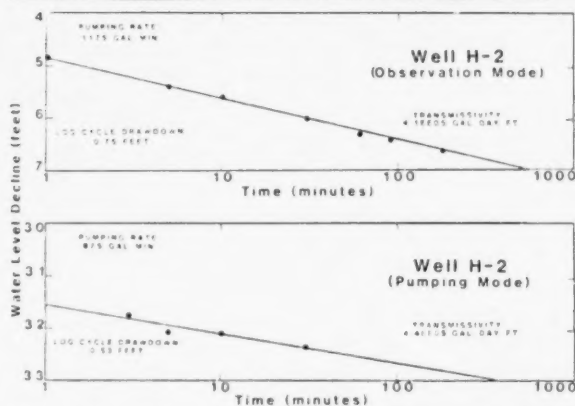


Figure 2. Drawdown-time plots for July 24, 1981, pumping test

Methodology

The proposed combined chemical time-series study and pumping test was conducted by the lead author on July 24, 1981. Well H-1 and Well H-2 had been inoperative for 12 hours and 72 hours, respectively, prior to commencing the tests to allow the aquifer to locally resume its original static water-level elevation(s). To initiate the tests, the static water levels in both wells were measured and the pump in Well H-1 was started. Water-level elevations in both wells were subsequently measured at 1, 5, 10, 30, 60, 90, 180 and 300 minutes of pumpage, and the discharge from Well H-1 was maintained at a constant 1,175 gpm. Samples for volatile organic analyses were taken in duplicate from a tap at the well head of Well H-1 concurrent with the 1-, 5-, 10-, 30-, 60-, 180- and 300-minute water-level measurements.

Sample collection and handling protocols for volatile organic analyses of drinking water were still evolving at EPA at the time of the test, but the general trend was to adhere as closely as possible to procedures outlined by EPA's "Sampling and Analysis Procedures for Screening of Industrial Effluents for Priority Pollutants," issued by the Agency as a result of the consent decree of

NRDC vs. Train. That is, specially prepared 40mL glass vials with Teflon-faced septa in screw closures were filled so that air bubbles were excluded; the samples were immediately tagged and listed on field data sheets and chain of custody forms and the samples were stored on ice for same-day transport to the Region 10 EPA Laboratory in Manchester, Washington. There they were analyzed by GC-Hall Conductivity Detector and GC-MS instruments.

[As a side note, given the tacit adoption of industrial effluent sampling procedures for all of the Agency's "priority pollutant" samples that has occurred in recent years, the interested reader may wish to peruse an excellent historical perspective and summary of priority pollutant sample collection and handling procedures by Branter and others (1981)].

Lakewood Water District had expressed an interest in determining the quality of water discharged from its alternate supply well, Well H-2, so the pump in that well was started a few minutes after the last (300-minute) measurement and samples were taken from Well H-1. Because it seemed useful from a geohydraulic standpoint to allow Well H-2 to attain equilibrium conditions and gain insights from its hydraulic interference with Well H-1, measurements of water levels in both wells were taken at 1, 5, 10 and 30 minutes since the onset of pumpage, with Well H-2 constantly discharging 875 gpm. By that time, equilibrium conditions were apparent (Figure 2), so the tests were terminated by shutting down both wells.

Samples for volatile organic analysis were collected from Well H-2 concurrent with the water-level measurements. The reasoning behind this was that it would be useful to provide a chemical time-series pattern from Well H-2 for comparison with data obtained from Well H-1. The nature of the contaminant source might be more readily discernible by such a comparison, should the contaminants not originate from inside Well H-1. Well H-2 had not undergone maintenance similar to Well H-1, so there was no reason to believe it might have residues of solvents/volatile organics internally as a result of cleaning the pump column, etc.

Results

Figure 2 shows that the transmissivity of the aquifer is approximately 4.1×10^5 gpd/ft using Jacob's equilibrium form of the Theis Equation to evaluate drawdowns observed in Well H-2 while Well H-1 was pumping. The virtual lack of roll-on or significant slope changes is justification enough for assuming that equilibrium conditions prevailed; the high-transmissivity value and low storage coefficient ($<10^{-4}$) also lend support ($u = r^2 S/4Tt = 0.00014$ or 1.4×10^{-5}). Moreover, a best-fit plot of additional drawdown generated by Well H-2 itself during subsequent testing (also Figure 2) yields a transmissivity of 4.4×10^5 gpd/ft, in good agreement with that from Well H-1 pumpage.

During construction of Well H-1, the transmissivity estimate had been shown to increase rapidly due to development by surging and overpumping (Robinson 1951). At the time it was put into service, the transmissivity was estimated to be 4.1×10^5 gpd/ft. In the course of constructing Well H-2 some eight years later, it was noted that the capacity of Well H-1 substantially increased during efforts to develop Well H-2 by overpumping; Well H-1 was noted to pull dirty water for a brief period at that time, presumably by removing fines loosened from the work on Well H-2 (Robinson 1959). The USGS analyzed pumping test data for Well H-1 with

its increased capacity and estimated transmissivity to be 9.3×10^{-4} gpd/ft (Griffin and others 1962). It would seem then that continual removal of fines from the glacial outwash aquifer over the years has resulted in raising the estimated transmissivity value based on Well H-1 pumpage from 4.1×10^{-4} gpd/ft to 4.1×10^{-5} gpd/ft, or one order of magnitude. Regardless of which estimate is held to be most representative of local conditions, the aquifer is certainly highly transmissive, as expected from the lithology of the production zone described by the drillers (Figure 1).

The USGS (Griffin and others 1962) gave a generalized water-table contour map for the Tacoma-Lakewood area which indicated that the local gradient at the Lakewood wells was approximately 25 feet per mile. The data generated in this study suggest it may be as low as 10 feet per mile locally. Using these bounds, an average transmissivity of 4×10^{-5} /ft, an estimated effective porosity of 0.25 and a saturated aquifer thickness of 100 feet, the ground-water flow velocity locally would be somewhere between 4 and 10 feet per day. The observations made during this study concerning the direction of flow agree with those of Griffin and others (1962); it is toward the northwest (magnetic bearing approximately 295 degrees). Well H-2 lies north-northwest (magnetic bearing 320 degrees) of Well H-1, so that ground-water flow generally proceeds from Well H-1 toward Well H-2 in the absence of pumping. As will be shown later, this is a significant factor in interpretation of the chemical time-series results for source identification, because of the upgradient-downgradient relationship between the two wells.

Figure 3 is a graphical presentation of the concentrations of the volatile organics found in the samples collected from Well H-1 on July 24, 1981. It is quite clear that the contaminant concentrations did not rapidly decrease, as postulated for internal contamination of Well H-1 by solvent residues. On the contrary, the contaminant concentrations rapidly increased and appeared to level off after only a few hours of pumpage. These chemical time-series patterns would seem to implicate an external source of contamination.

Figure 4 gives similar indications for Well H-2, but at markedly higher initial and subsequent concentrations. Does this mean that the source is closer to Well H-2? A hydraulic divide was formed by operating both wells simultaneously while sampling Well H-2, but no samples were taken from Well H-1 during that portion of the test: 20/20 hindsight suggests that such samples would have been invaluable. Given the data limitations, conclusions cannot be drawn as to whether the contaminants lay primarily on one side of the hydraulic divide or the other—a piece of information that Lakewood Water District could use to help manage its water quality. If contaminants lay primarily on one side of the hydraulic divide, a temporary solution would be to use water discharged from the "cleaner" well for supply purposes and waste water discharged from the more contaminated well.

To resolve this uncertainty, a follow-up sampling was conducted August 8, 1981. Both wells had been inoperative since the previous test and were started simultaneously. After 10 hours of pumping, duplicate volatile organic analysis samples were obtained from each well (Table 1). The picture now seemed quite clear: the higher, most troublesome levels of the contaminants were available only to Well H-2. Further reflection on the ramifications of these data and the July 24, 1981, study suggested that the source of the contaminants was not

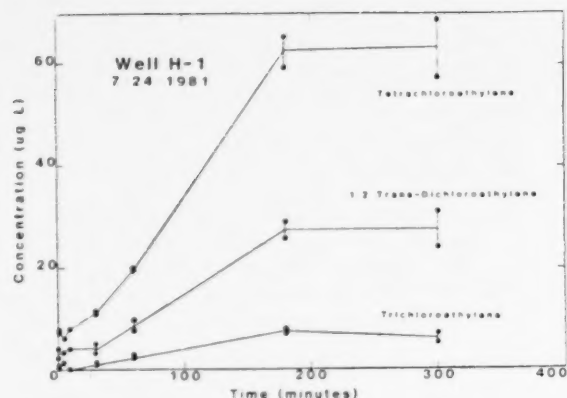


Figure 3 Chemical time-series plot for Well H-1 samplings, July 24, 1981

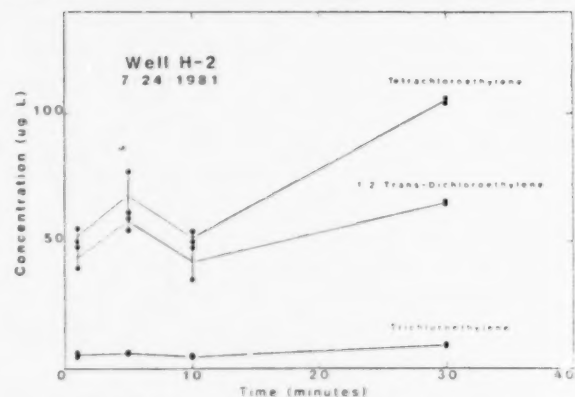


Figure 4 Chemical time-series plot for Well H-2 samplings, July 24, 1981

Table 1
Volatile Organic Concentrations in Well H-1 and Well H-2 on August 8, 1981 (in $\mu\text{g/L}$)

Contaminant	Well H-1	Well H-2
Tetrachloroethylene	31	196
(duplicate)	(43)	(272)
Trichloroethylene	3.8	20
(duplicate)	(3.6)	(15)
1,2 Trans-Dichloroethylene	6.5	101
(duplicate)	(15)	(86)

only on the Well H-2 side of the hydraulic divide, but was probably downgradient of Well H-2 itself.

Such a source location would allow for the obvious differences in contaminant concentrations, and would also explain the high initial levels with the onset of pumpage at Well H-2 after pumping Well H-1 for several hours. The contaminants would be drawn from beyond Well H-2 toward Well H-1, bathing Well H-2 in higher concentrations with increased contaminant levels. It would not be so coincidental, then, that the initial contaminant levels in Well H-2 should be so near to the final concentrations in Well H-1 (compare Figure 3 with Figure 4). A hypothetical illustration of this mechanism of contaminant distribution has been given earlier (Keely 1982); it has been modified here to lend more specificity to the example being discussed (Figure 5).

Since the aforementioned scenario was not the only one which could reasonably give the results observed during the tests, other hypotheses were advanced. In particular, it was noted that a perched water table would probably lay atop the semi-confining till layer (assumed to be unsaturated) and that Well H-2 did not have the same annular grouting through the till layer that Well H-1 did. Instead, Well H-2 had a pea gravel jacket surrounding the casing, which was installed because of excessive caving of the formation while pulling back temporary drive casing (Robinson 1959). The EPA Regional Geologist, Jack Sceva, postulated that this might be a ready conduit for contaminated water from a perched aquifer to reach Well H-2 in the highest concentrations. In order to test either hypothesis, monitoring wells had to be installed.

Figure 6 is a generalized location map showing the relative positions of Well H-1, Well H-2, several shallow wells installed to test the quality of the uppermost portion of the saturated zone and several deep wells installed to test the quality of the production zone. The monitoring wells were installed under the supervision of the Ecology and Environment field team, who also conducted detailed pump tests and additional chemical time-series samplings (Wolf and Boateng 1983). These pump tests confirmed earlier indications of the high transmissivity and semi-artesian nature of the production aquifer.

Two years and some 33 monitoring wells after the investigation was first initiated, the authors have concluded that the glacial till layer is discontinuous, but is saturated and has localized ground-water lenses overlying it and these lenses are intimately hydraulically connected with the production zone. The contaminants affecting Well H-1 and Well H-2 do not originate in the shallow lenses atop the till in the immediate vicinity of these supply wells. Rather, the contaminant source is

approximately 475 feet away along a true bearing of 12 degrees (351 degrees magnetic, with 21 degrees easterly variation locally) from Well H-2, or 400 feet downgradient and 260 feet cross-gradient. There, septic tank effluent rich in solvents from a dry cleaning establishment has been filtering down through the discontinuous semi-permeable glacial till to reach the production aquifer. The pumping action of the Lakewood supply wells has been sufficient to locally reverse the natural gradient, causing the contaminants to move upgradient and cross-gradient with respect to pre-pumping conditions. Table 2 is a summary of the most recent sampling of all wells for volatile organic analyses. By comparison of the data presented there with the generalized well locations shown in Figure 6, it is evident that the only monitoring wells with detectable contaminant levels are those which are immediately adjacent to and down-gradient or cross-gradient from the pumping wells (11, 24, 15, 16, 20 and 21).

Distance of Draw and Capture Zone

The methods presented by Keely (1982) and Keely and Tsang (1983) for estimating contaminant travel in response to pumpage were used to check initial time-series test interpretations and the assertion that either supply well could locally reverse the natural gradient and cause effluent-contaminated water to flow 400 feet upgradient and 260 feet cross-gradient to the pumping well(s). The first of the two methods (Keely 1982) ignores the effect of the natural ground-water flow velocity on the manner in which water is drawn into a well by pumping; it assumes equal velocity of travel radially toward the well at any select distance. This is an acceptable approach for crude estimation, particularly when reliable data are not available as to the direction and magnitude of the natural flow velocity. The author notes that the method is a rough estimation technique only (Keely 1982), and most useful for short pumping periods where the estimated distance of draw (contaminant travel) falls short of reaching the point where the drawdowns caused by pumpage are offset by the

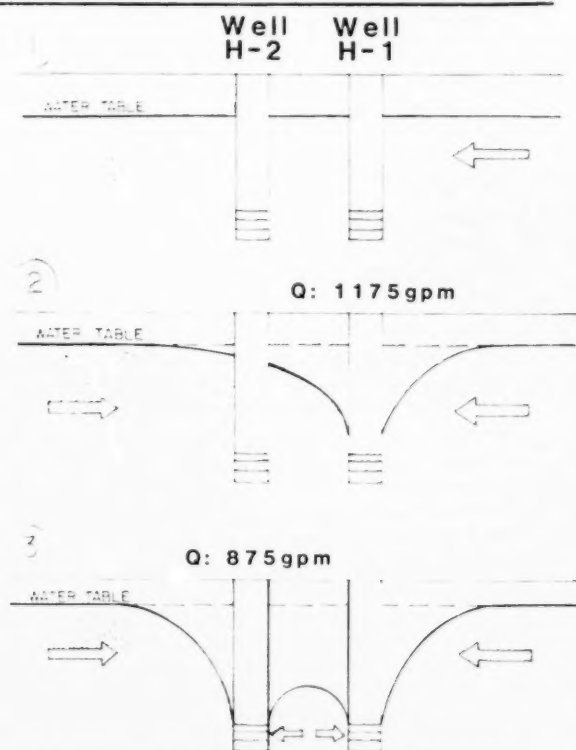


Figure 5. Contaminant plume isolation by hydraulic interference between Well H-1 and Well H-2

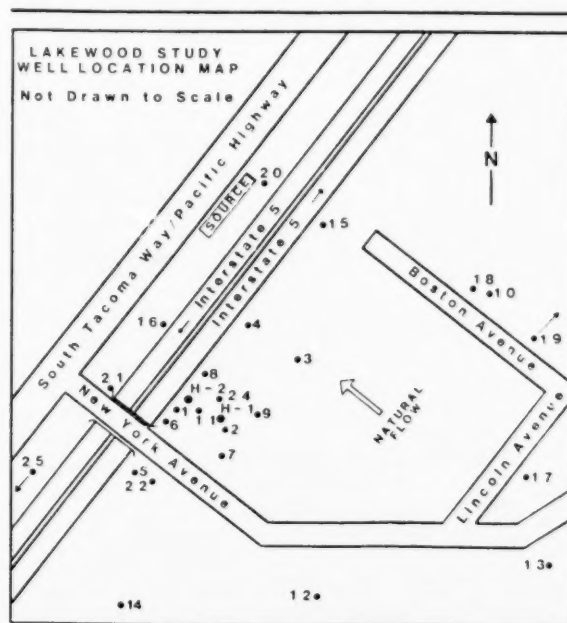


Figure 6. Location map of monitoring wells installed for source identification

Table 2
Spring 1983 Survey Results of Volatile
Organic Analyses of Lakewood Study Wells

Date	Well No.	1, 2(trans) dichloro-ethylene ($\mu\text{g/L}$)	Trichloro-ethylene ($\mu\text{g/L}$)	Tetrachloro-ethylene ($\mu\text{g/L}$)
02-02-83	1	1.5	1 M	1.6
02-03-83	2	—	—	—
02-01-83	3	—	—	—
01-31-83	4	1 M	—	1 M
01-31-83	5	—	—	—
02-03-83	6	1 M	—	1 M
02-02-83	7	—	—	—
02-01-83	8	1 M	—	1 M
02-01-83	9	—	—	—
01-31-83	10	—	—	1 M
02-02-83	11A	9.2	—	1 M
02-02-83	11B	5.6	1 M	1 M
02-03-83	12	—	—	—
02-01-83	13A	—	—	—
02-02-83	13B	—	1 M	—
02-03-83	14	—	—	—
02-03-83	15A	26	4.0	96
02-03-83	15B	100	4.7	60
02-04-83	16A	188	6.7	76
01-04-83	16B	14	1 M	4.0
02-07-83	17A	—	—	1 M
02-07-83	17B	—	—	—
02-23-83	18	—	—	1 M
02-23-83	19A	—	1 M	1 M
02-23-83	19B	—	—	1 M
02-04-83	20A	179	23	632
02-04-83	20B	485	43	362
02-07-83	21	41	1.9	19
02-03-83	22	—	—	—
02-03-83	24A	202	22	522
02-02-83	24B	224	25	517
02-23-83	25	—	—	—
02-02-83	H-1	268	26	417
02-02-83	H-2	220	25	345

1 M Above the background sensitivity but not quantifiable.

— Below the detection level ($0.1 \mu\text{g/L}$).

Well 23 does not exist; it was abandoned immediately after installation at the property owner's request.

natural gradient (e.g., velocity of pumping - natural velocity).

For the Lakewood wells this method was employed to give a first order approximation of the average distance traveled by the contaminants during the 300-minute chemical time-series test of Well H-1 on July 24, 1981. Assuming an effective porosity of 0.25 and an effective aquifer thickness of 65 feet (tight till and silts occupy 35 feet of the 100-foot saturated thickness), this calculation resulted in an estimated value of 30 feet traveled during the test. Given the maximum natural flow velocity of 10 feet per day described earlier, Well H-1 could have been inoperative at least three days prior to the test and still pulled in some contaminants. The best estimate of natural flow velocity (at 4 feet per day) and the actual down time of 12 hours implies that contaminants may have been as close as 2 feet downgradient of Well H-1. It would then have pulled in contaminants

almost immediately, in agreement with our observations.

The second method, presented by Keely and Tsang (1983), incorporates the effect of the natural flow velocity on pumpage patterns and contaminant travel times; it yields a distribution plot of the velocity field for the combination of pumping and natural flow velocities. Using this method, estimates of the downgradient stagnation point and cross-gradient lateral limit of the capture zone (portion of the aquifer contributing water to the well) of each pumping well were prepared. For Well H-1, the downgradient stagnation point was estimated to be 554 feet, assuming natural flow velocity of 4 feet per day. The lateral limit, a maximum of π times the stagnation point value, equaled 1,740 feet. The corresponding values for Well H-2 were 412 feet to the downgradient stagnation point, and 1,295 feet to the lateral stagnation point. The contaminant source, which is only 400 feet downgradient and 260 feet cross-gradient from Well H-2 could easily be drawn to either well. To underscore the implications of these conservative/idealized estimates, Wolf and Boateng (1983) noted that the generally anisotropic nature of these glacial deposits as previously described by Walters and Kimmel (1968) was particularly pronounced locally, with the major transmissivity axis generally oriented parallel to the natural flow direction.

Tracers, Timing and Troubles

The use of chemical time-series sampling is quite similar to the use of tracer tests to gain insights into preferential paths of contaminant movement. Davis and others (1980) define a tracer as "matter or energy carried by water which will give information concerning the direction and/or velocity of the water, as well as potential contaminants which could be transported by the water... A tracer can be entirely natural such as the heat carried by a plume of geothermal water, it can be accidentally introduced such as chlorides leached from a landfill, or it can be introduced intentionally such as dyes placed in sink holes..." Since the time of release and the input concentration of intentional tracers are known for traditional tracer tests but unknown for contaminant studies, the interpretation of data from chemical time-series sampling might initially seem to be severely hampered. However, it is the pattern of relative concentrations over time which are actually examined in either case. The absolute values are neither required nor are they all that readily obtainable even under the best controlled field tests. There are simply too many avenues for tracer losses (sorption, ion-exchange, biodegradation, etc.) to allow for proper mass balancing.

Preferential paths of flow and contaminant transport are determined by frequent samplings at several locations regardless of whether one is conducting a traditional tracer test, a conventional contaminant investigation or a chemical time-series sampling study. The prime difference between conventional surveys and the approach advocated here is simply timing. One can take the conventional approach of sampling an array of monitoring wells several times over a period of months, allowing the natural system to slowly move a contaminant plume, or one can accelerate the natural system by pumpage and gain similar information by rapidly collecting a succession of samples.

There are sound benefits to incorporation of successive pumped samples in ground-water contaminant investigations other than temporal sampling efficiency.

however. It has been shown here that concurrent hydraulic testing not only yields important information about aquifer parameters, but may be readily adapted to enhance the use of time-series analyses; e.g., purposeful hydraulic interference can be used to isolate and locate a contaminant source. Keely and Tsang (1983) describe simple equations which can be used to examine the time-series patterns of contaminant concentrations at pumping and nonpumping monitoring wells alike. Keely (1982) had previously noted that the full power of chemical time-series sampling required a mixture of both pumping and nonpumping monitoring wells. As water was withdrawn by a pumping well, the surrounding water would move toward it and would travel by or through nearby monitoring wells—yielding useful time-series patterns at those wells. Keely and Tsang (1983) show how such patterns may be combined to produce pictures of the spatial distribution of contaminants and how that distribution changes with time.

Keely (1982) also notes that the increased size of aquifer volume sampled is a major benefit, particularly with regard to ensuring proper representation of the quality of aquifer waters. He suggests some implications that the chemical time-series data technique has for borehole purging efforts and comparison of data gathered from wells purged and pumped of dissimilar volumes; the data are not directly comparable and so should not be contoured for interpretation purposes. It is further suggested here that the popular method of ensuring representation by sampling only after withdrawn water has reached stable pH, conductivity and

temperature values is adequate for regional/ubiquitous contaminants, but inadequate for localized plumes. In support of this contention, it was consistently shown during the Lakewood study that pH, conductivity and temperature stabilized very quickly whereas organic contaminant concentrations were continuously variable throughout the tests (e.g., Figure 3, 4, 7 and 8). Can one ever purge enough water to reach stable contaminant levels in such cases? The answer to this question is "no." A single sample cannot convey the information needed, the sense of inherent variability. Rather, the single sample is a needle in the temporal haystack, just as a nonpumping monitoring well alone is a needle in the spatial haystack.

Summary

Given the difficulty of locating a contaminant source by nonpumping monitoring well installations alone, it now seems that greater confidence in the chemical time-series patterns and associated hydraulic testing was warranted for the Lakewood study. Still, hindsight should not lure one into a false sense of security and overconfidence. A prudent mixture of some non-pumping monitoring wells and the pumping wells will always yield the best results. Consider, for example, the difficulty of interpreting Figures 7 and 8 without additional monitoring wells, which show the results of extended chemical time-series samples collected by the Ecology and Environment field team from Well H-1 and Well H-2 during August 1982 and February 1983, respectively. The concentrations rise as they did during the July 1981 samplings, but fall rapidly after a few hundred

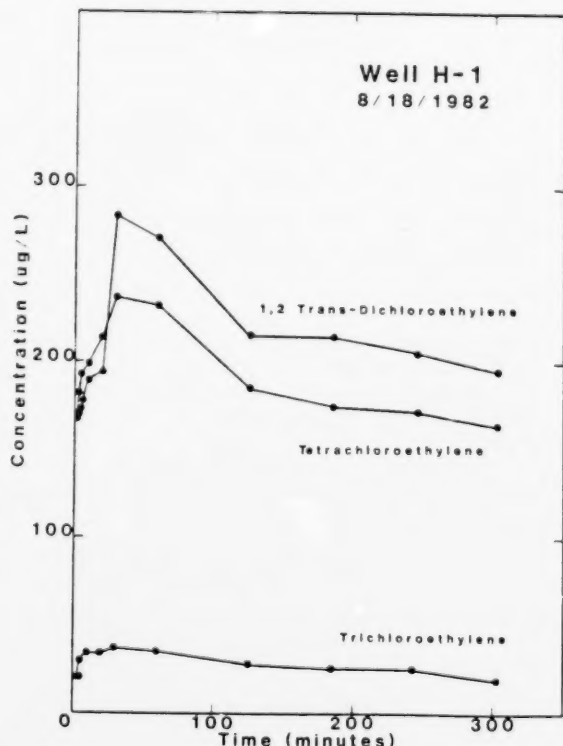


Figure 7. Chemical time-series plot for Well H-1 samplings, August 18, 1982

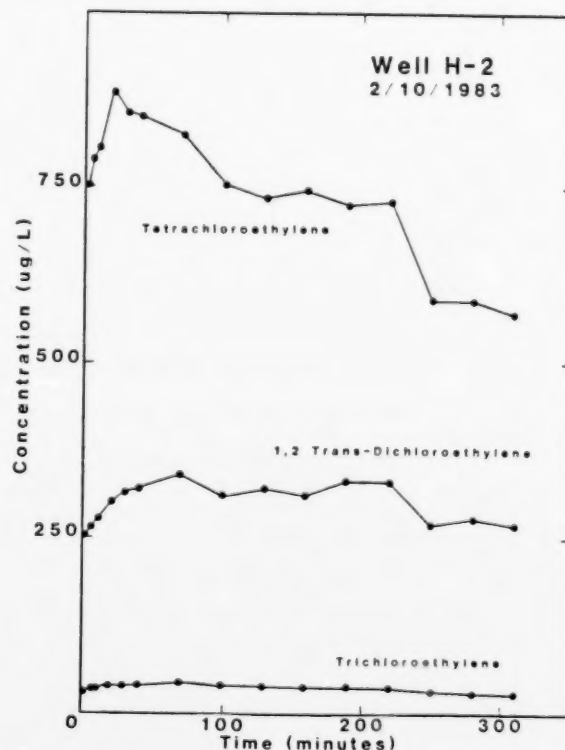


Figure 8. Chemical time-series plot for Well H-2 samplings, February 10, 1983

minutes of pumping.

What are the implications of these curves? Is the transient nature of the contaminant loadings a result of sporadic release to the aquifer by occasional deep percolation of the dry cleaning septic waste, due to rainfall or irrigation events, similar to the cyclic effects described by Pettyjohn (1982)? Is it a matter of spatially varied sorptive properties of the aquifer due to changes in the particle sizes of the aquifer solids as suggested by Rea and Upchurch (1980), but which may also change with time because of the need to establish new equilibria with sorption sites accustomed to other species as suggested by Reardon (1981)? Perhaps biodegradation has taken its toll. Surely resolution of which mechanisms are governing the shape of the chemical time-series patterns in Figures 7 and 8 requires installation of additional monitoring wells (pumping or not); those data are insufficient for stand-alone interpretations.

Such uncertainties and interpretive difficulties reduce chemical time-series sampling to what it truly is: simply another useful tool for the contaminant hydrologist, another method that may generate insights to help piece the puzzle together. It is not a panacea any more than the exclusive use of nonpumping monitoring wells is. It may result in increased efficiency and lowered economic costs for ground-water contamination investigations (Keely 1982), but it takes common sense and hydrologic intuition to be properly applied, just like any other investigative technique available today.

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Disclaimer

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Biographical Sketches

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